GENERAL THORACIC SURGERY

COMPARISON OF EARLY FUNCTIONAL RESULTS AFTER VOLUME REDUCTION OR LUNG TRANSPLANTATION FOR CHRONIC OBSTRUCTIVE PULMONARY DISEASE

Background. Bilateral lung volume reduction is designed to improve pulmonary function in selected patients with severe emphysema by improving diaphragmatic and chest wall mechanics. Early results of lung volume reduction suggest significant improvement to selected patients with chronic obstructive pulmonary disease, some of whom might otherwise be considered for lung transplantation. The purpose of this review was to compare intermediate results of volume reduction with single and bilateral lung transplantation. *Methods.* Functional performance and survival after volume reduction were compared with single and bilateral sequential lung transplantation. After evaluation, patients were enrolled in a supervised intensive preoperative and postoperative program of pulmonary rehabilitation. Functional assessment, including pulmonary function tests, room air arterial blood gas analysis, and 6-minute walk distance, was obtained before the operation and 3, 6, and 12 months after the operation. *Results.* Thirty-three patients underwent volume reduction (mean age 57 years), 39 patients single lung transplantation (55 years), and 27 patients bilateral lung transplantation (49 years). Early mortality was 0, 1 of 39, and 2 of 25 and mortality at 12 months was 1 of 33, 4 of 39, and 4 of 25 in the volume reduction, single, and bilateral lung transplantation groups, respectively. At 6 months, mean forced expiratory volume in 1 second was improved by 79% (volume reduction), by 231% (single lung transplantation), and by 498% (bilateral lung transplantation) over preoperative values. Exercise endurance as measured by 6-minute walk distance increased by 28% (volume reduction), by 47% (single lung transplantation), and by 79% (bilateral lung transplantation) from baseline. At 6 months, all patients having single or bilateral lung transplantation and 26 of 33 patients having volume replacement were free of supplemental oxygen. *Conclusions.* Although single and bilateral lung transplantation result in superior lung function, volume reduction achieves satisfactory improvement of disabling symptoms early after operation while avoiding immunosuppression and transplant-specific complications. Our experience suggests that (1) volume reduction is a suitable alternative in selected patients eligible for transplantation; (2) volume reduction provides an earlier option for treatment in patients who may require transplantation at some future date; (3)

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volume reduction is the only surgical treatment available to the many patients who are not current or future transplant candidates. Conversely, in patients not suitable for volume reduction, transplantation remains the only choice for surgical therapy. (J THORAC CARDIOVASC SURG 1996;111: 296-307)

During the past decade pulmonary transplantation has evolved into a successful treatment for patients with end-stage emphysema. Patients with chronic obstructive pulmonary disease (COPD) constitute the single largest group of lung transplant recipients. Among recipients with emphysema, single and bilateral lung transplantation are associated with satisfactory early morbidity and mortality.[1] In addition, significant physiologic improvement is achieved.[2] However, a critical shortage of suitable donor lungs restricts the transplant option to a small number of eligible patients. Furthermore, many patients with COPD are considered ineligible for lung transplantation because of age or other comorbid conditions such as coronary artery disease. Most lung transplant recipients have significant morbidity as a result of the mandatory immunosuppressive protocol. Long-term survival continues to be adversely affected by chronic rejection[3] and other complications. Because these limitations are expected to persist, alternate treatment strategies are desirable in patients with diffuse emphysema.

The concept for surgical reduction of lung volume was reported previously by Brantigan, Mueller, and Kress.[4] Recent advances in pulmonary rehabilitation, anesthetic technique, and surgical instrumentation have made surgery for reduction of bilateral lung volume a practical alternative.[5] Ideal candidates for volume reduction have (1) significant thoracic hyperinflation with a flattened diaphragm and decreased chest wall excursion and (2) regions of severe destruction that occupy a large volume with little perfusion, providing target areas for resection. The term *volume reduction* has been applied to this procedure because it consists of multiple wedge resections (20% to 30% of lung volume bilaterally) and results in a reduced total lung capacity and radiographically measurable improvement of chest wall distention and diaphragmatic excursion.[1] These improvements in turn improve ventilation to the more normal, although less compliant, regions of the lung. Although the patient is left with emphysematous lungs, the postoperative problems of transplantation, in particular rejection and immunosuppression, are avoided.

Our patient selection criteria for lung transplantation obviously include the absence of alternative therapy. The preliminary results from volume reduction suggest that this procedure may offer significant improvement to some of the patients with COPD who might otherwise be considered for lung transplantation. The purpose of this review was to determine whether the early results of lung volume reduction justify its use as an alternative to lung transplantation, even if the improvement after volume reduction proves to be of limited duration. Selection criteria for lung transplantation and volume reduction are not identical. No attempt is therefore made to identify the "better" operation, but rather to provide a preliminary assessment of their relative roles in the treatment of patients with emphysema.

Methods

This report is a retrospective analysis of our results after three surgical procedures for advanced COPD: volume reduction, single lung transplantation, and bilateral sequential lung transplantation. Patients with α_1-antitrypsin deficiency were excluded from this analysis, because we have only recently applied volume reduction to patients with this condition and sufficient follow-up for analysis is not yet available. Volume reduction was introduced at our institution in January 1993. With increasing experience, we offered volume reduction to patients who, by virtue of age less than 65 years and forced expiratory volume in 1 second (FEV_1) less than 20% of predicted,might otherwise have been eligible for lung transplantation. Indeed, five of the patients in the volume reduction group (described in the next section) were listed for lung transplantation. The first such patient underwent volume reduction in December 1993. We have restricted this analysis to patients in whom postoperative follow-up for at least 6 months is available.

Volume reduction. Patients with advanced, diffuse emphysema and severe exercise restriction were evaluated. Criteria important for selection were severe dyspnea, distention of the thorax, and heterogeneous distribution of disease, typically with predominant destruction of the upper lobes. These conditions provide the opportunity of "downsizing" lungs without sacrificing functioning lung tissue. All patients were judged to have residual lung with relatively preserved architecture. Patients with complete destruction of the entire lung were not offered volume reduction. At the current time, we are uncertain as to exact selection criteria with regard to spirometric values, diffusing capacity, hypoxia, or hypercarbia. However, we believe that patients with an FEV_1 less than 15% of predicted, marked hypoxemia (necessitating more than 6

L of supplemental oxygen at rest), or severe hypercarbia (arterial carbon dioxide tension > 55 mm Hg) usually have such a degree of parenchymal lung destruction that volume reduction is not advisable. Patients were excluded from consideration in the presence of pulmonary hypertension (mean pulmonary artery pressure > 35 mm Hg, systolic pulmonary artery pressure > 45 mm Hg), severe kyphosis, severe left ventricular dysfunction, previous pleurodesis, age older than 80 years, asthma, severe chronic bronchitis, or bronchiectasis. Evaluation included inspiratory and expiratory posteroanterior and lateral chest radiographs, chest computed tomographic scintigraphy, and quantitative nuclear ventilation-perfusion scintigraphy. Additional assessment consisted of pulmonary function studies, arterial blood gas analysis with the patient breathing room air, 6-minute walk distance, and dyspnea index (discussed later). Suitable candidates were enrolled in a supervised exercise program for at least 6 weeks before the operation. A clear rehabilitation goal was set for each patient. With few exceptions, the operation was not performed unless this goal had been met. Bilateral volume reduction was performed through a median sternotomy as previously described.[5]

Ninety patients underwent volume reduction between January 1993 and April 1995. Thirty-three of these have completed more than 6 months of follow-up and comprise the volume reduction group in this report. Eighteen of these 33 patients have completed more than 1 year of follow-up. Among all patients undergoing volume reduction before February 1995, we identified five patients who were actually listed for transplantation and seven who were considered for transplantation but instead were referred to us for volume reduction. Data from these 12 patients will be presented separately in this article.

Lung transplantation. Patients were selected for lung transplantation according to previously published criteria.[6] These criteria were more strict than those for volume reduction with regard to age (<65 years), cardiac performance (absence of significant left ventricular dysfunction or coronary artery disease), and nonpulmonary organ dysfunction. Graded exercise training (discussed later) was instituted at the time of listing for transplantation. The conduct of this training was identical to that used before volume reduction, but its duration was usually longer because of the wait for a donor organ. Recipients were allocated to single or bilateral transplantation according to age, body size, and lung donor availability.

Between March 1989 and April 1994, 64 patients underwent lung transplantation for COPD. Thirty-nine patients had single lung transplantation performed via posterolateral thoracotomy. Twenty-five patients underwent bilateral sequential lung transplantation via bilateral anterior thoracosternotomy. Standard techniques of donor harvest[7] and allograft implantation[8, 9] were used. Immunosuppression consisted of cyclosporine, corticosteroid, azathioprine, and induction therapy with antilymphocyte globulin. These single and bilateral lung transplant recipients do not represent an experience contemporaneous with the patients undergoing volume reduction; rather, they are a group of consecutive patients in whom at least 6 months of follow-up was available at the time of analysis.

Pulmonary rehabilitation. Preoperative pulmonary rehabilitation was instituted to improve exercise endurance.[10] Patients exercised on the treadmill or on a bicycle ergometer three to five times per week to achieve 30 minutes of continuous exercise at a heart rate of 85% of the predicted maximum heart rate for the patient's age. Supplemental oxygen was administered as necessary to maintain oxygen saturations of greater than 90% during exercise. Arm ergometry served to condition upper extremity strength as needed and was used as an alternative to the treadmill for patients whose gait was limited by peripheral vascular disease or orthopedic/arthritis problems.

Postoperative pulmonary rehabilitation was used to restore exercise capacity, assist in airway clearance, and increase chest wall mobility. Short walks were resumed during the first postoperative days. When the patient was able to walk 2000 to 3000 feet per day after the operation, treadmill exercise was resumed. After volume reduction, patients continued their pulmonary rehabilitation program at our pulmonary rehabilitation facility for 1 week after discharge. Thereafter, rehabilitation was continued in the patients' own community. Lung transplant recipients attended our rehabilitation facility five times per week for 3 months after discharge before returning to their own community program.

Follow-up studies. Follow-up pulmonary function studies, analysis of arterial blood gases with the patient breathing room air, and determination of 6-minute walk distance were obtained at 3-, 6-, and 12-month intervals. The oxygen requirements at rest and during exercise were recorded.

At the time of evaluation, the degree of dyspnea was assessed with the use of the baseline part of the dyspnea index published by Mahler and associates.[11] This index consists of three descriptive components. *Functional impairment* deals with performance in daily social and professional activities, *magnitude of task* grades the load that leads to shortness of breath, and *magnitude of effort* grades the individual degree of exertion that results in dyspnea. Every component has grades ranging from 0 to 4, and the final score adds the three grades from each component. The baseline dyspnea index has a potential score from 12 (no impairment) to 0 (severe impairment).

Statistical analysis. Data were analyzed by means of a repeated-measures analysis of variance with the SAS program.[12] Selected time and group differences were investigated with pairwise *t* tests on the least-squares means.

Results

Patients in all three groups were profoundly restricted by their disease, although the degree of physiologic impairment was less severe in the volume reduction (VR) group than in the single lung (SLT) or bilateral lung transplant (BLT) groups. Patients undergoing volume reduction had a higher mean FEV_1, a longer walk distance in 6 minutes at the time of evaluation and after preoperative pulmonary rehabilitation (VR, 1131 feet; SLT, 1036;

Table I. *Patient profile at evaluation*

	Volume reduction	*Single lung transplantation*	*Bilateral lung transplantation*
No. of patients	33	39	25
Mean age (yr)	57	55	49
Male/female	17:16	11:28	10:15
FEV_1 (L)	0.72 (±0.26)	0.48 (±0.12)	0.49 (±0.13)
FEV_1 (% of predicted)	25 (±7.3)	18 (±3.9)	16 (±4.5)
FVC (L)	2.25 (±0.82)	1.70 (±0.60)	1.83 (±0.79)
FVC (% of predicted)	63 (±19)	47 (±12)	47 (±17)
Pao_2 (mm Hg Fio_2 0.21)	62 (±9.7)	52 (±9.2)	56 (±8.5)
$Paco_2$ (mm Hg Fio_2 0.21)	42 (±7.6)	49 (±9.9)	46 (±8.4)
Six-minute walk distance (feet)	917 (±351)	703 (±254)	830 (±309)
Baseline dyspnea index	3.2 (1-6)	3.1 (0-6)	3.6 (0-6)

Functional and blood gas data are expressed as mean values (± standard deviation). Pulmonary function data represent best values achieved, with or without a bronchodilator. *FEV_1*, Forced expiratory volume in 1 second; *FVC*, forced vital capacity; *Pao_2*, arterial oxygen tension; *Fio_2*, inspired oxygen fraction; *$Paco_2$*, arterial carbon dioxide tension.

Table II. *Early and late mortality after volume reduction, single, and bilateral lung transplantation*

	Volume reduction	*Single lung transplantation*	*Bilateral lung transplantation*
Early (<30 days) mortality	0% (0/33)	2.5% (1/39)	8.0% (2/25)
Cause of death	—	Allograft failure	Intraop. hemorrhage Myocardial infarction
Late (30 day to 1 year) mortality	3.0% (1/33)*	7.7% (3/39)	8.0% (2/25)
Cause of death	Heart failure s/p CABG at 3 mo	CsA-related neurotoxicity at 2 mo Aspiration pneumonia at 3 mo Lymphoproliferative disease at 3 mo	Lymphoproliferative disease at 7 mo Hemolytic-uremic syndrome at 9 mo
Total mortality	3.0% (1/33)*	10.2% (4/39)	16.0% (4/25)

*Follow-up to 1 year after volume reduction is available for 18 of 33 patients.
S/P, Status post; *CABG*, coronary artery bypass grafting; *CsA*, cyclosporine.

BLT, 974), higher room air oxygen tension, and lower oxygen requirement (Table I). Forty-five percent (15/33) of patients undergoing volume reduction were oxygen-dependent at rest and 88% (29/33) with exercise. Nineteen of 33 patients (57%) undergoing volume reduction were receiving oral steroids before the operation. Symptoms and limitations of dyspnea were similar for patients in all three groups. The mean baseline dyspnea index (VR, grade 3.3; SLT, 3.1; BLT, 3.6) indicated severe functional impairment (i.e., dyspnea occurring with light activities) and inability to work.

Patients on the transplant list accrued significant waiting periods. Recipients of bilateral lung grafts waited on average 8.3 months (SD* ± 2.8 months) and single lung recipients 5.8 months (SD ± 3.7 months) for their operation. In contrast, patients having volume reduction were operated on a mean of 2.6 months (SD ± 1.6 months) after their evaluation. Patients on the transplant list began their exercise program after being listed and continued until the time of transplantation. These patients reached a plateau in their walk distance from 6 weeks to 3 months after starting the program, with no further improvement of exercise endurance despite continued training.

Among the 33 patients undergoing volume reduction, there were no operative (30 day) deaths. One in-hospital death occurred 3 months after volume reduction (3.0%). After single lung transplantation, there was one perioperative death (2.5%) and three late deaths within the first year for an overall mortality of 10.2%. Operative and 1-year mortality rates after bilateral lung transplantation were each 8% (2/25), for a total mortality rate of 16%. Causes of death are listed in Table II. Mean hospital stay was 31 days (median 21 days) after single lung transplantation, 27 days (median 23 days) after

*SD = Standard deviation.

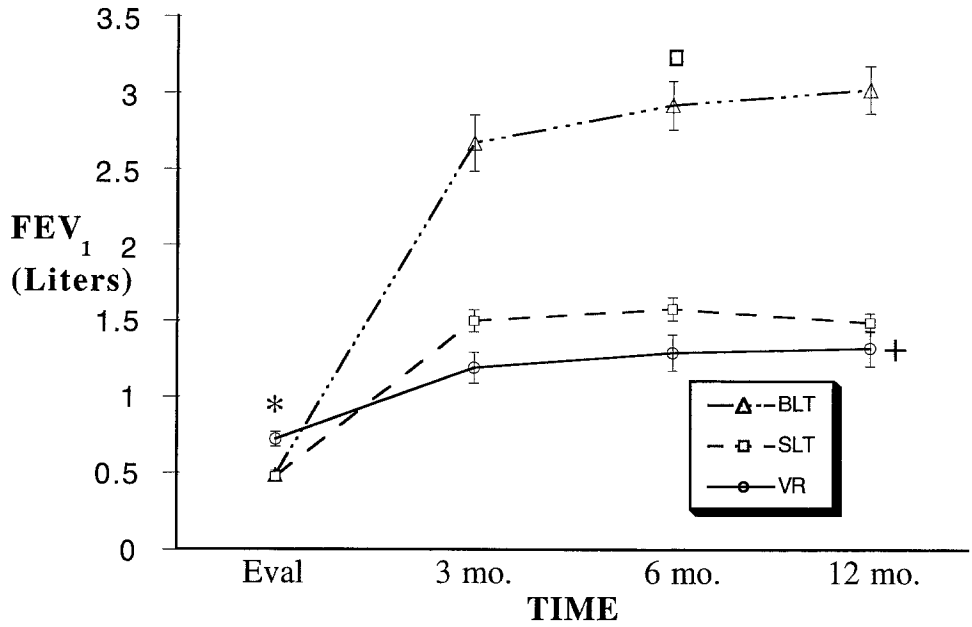

Fig. 1. FEV_1 before and after volume reduction *(VR)*, single lung transplantation *(SLT)*, and bilateral lung transplantation *(BLT)*. At evaluation (*): VR versus SLT, $p < 0.001$; VR versus BLT, $p < 0.001$. At 6 months (□), VR versus SLT, $p < 0.001$; VR versus BLT, $p < 0.001$. (+) VR Eval versus VR 6 mo, $p < 0.001$.

bilateral lung transplantation, and 16 days (median 13 days) after volume reduction.

The three procedures, volume reduction, single lung transplantation, and bilateral sequential lung transplantation, all resulted in improvement of physiologic parameters, exercise endurance, and gas exchange. At 6 and 12 months from the operation, mean FEV_1 had increased over preoperative values by 79% and 83% in the volume reduction group, by 231% and 212% in single lung transplant recipients, and by 498% and 518% in bilateral lung transplant recipients (Fig. 1). Fig. 2 depicts the percent of predicted FEV_1. A modest increase in forced vital capacity was observed, particularly in the bilateral lung transplant group, whereas the other patients showed a smaller increase (Fig. 3).

The 6-minute walk distance at 6 months was 28% greater than the preoperative distance (postrehabilitation) in the volume reduction group, 47% greater in the single lung transplant recipients, and 79% greater in the bilateral lung transplant recipients (Fig. 4). The postoperative exercise tolerance did not deteriorate in any patient group during the 1-year follow-up period.

Hypoxemia was improved after all three procedures. Whereas patients undergoing volume reduction had higher oxygen tensions while breathing room air and showed only a modest postoperative improvement, both single and bilateral lung transplantation caused markedly increased room air oxygen tensions at 3 months, with continued improvement in the group having bilateral transplantation (Fig. 5). With improved oxygenation, the use of supplemental oxygen decreased after operation. All patients awaiting lung transplantation were receiving supplemental oxygen at rest. Only one patient, after single lung transplantation, required supplemental oxygen at 3 months and no patients thereafter. In the volume reduction group, 29 patients (88%) required supplemental oxygen at exercise and 15 patients also required oxygen at rest. Although freedom from oxygen supplementation took longer to achieve after volume reduction, by 6 months only seven patients (21%) used oxygen during exercise and three at rest (Table III). One year after volume reduction, one of 18 patients (5.5%) was oxygen-dependent during exercise and none at rest. Lung transplantation also corrected preoperative hypercarbia within 3 months after the operation. Carbon dioxide retention in the volume reduction group was less prevalent, although carbon dioxide tensions were significantly lowered after the operation (Fig. 6).

We separately analyzed the data from 12 patients

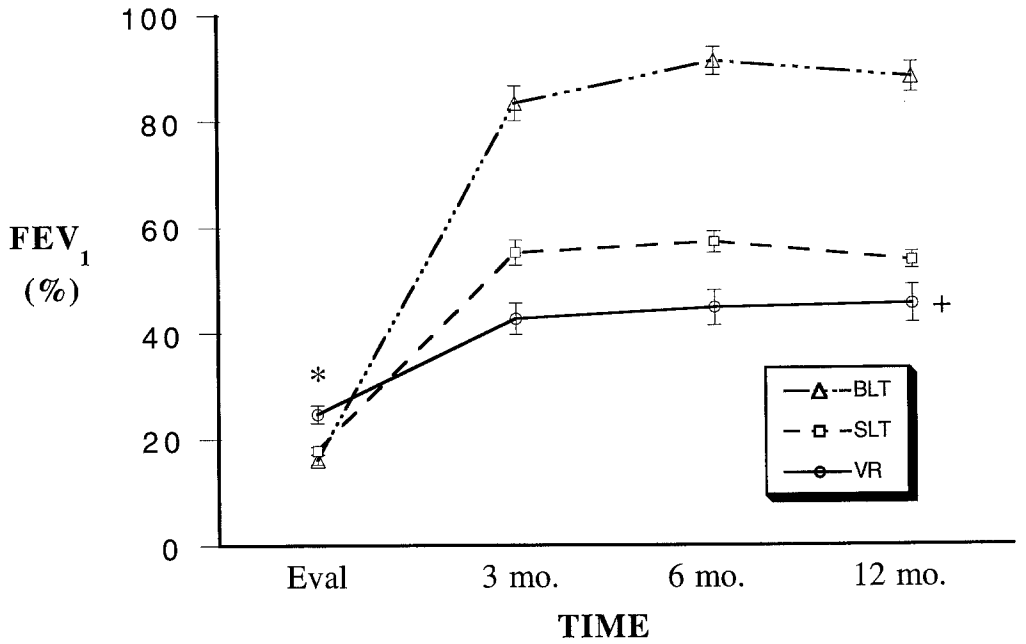

Fig. 2. Percent of predicted FEV_1 before and after volume reduction *(VR),* single lung transplantation *(SLT),* and bilateral lung transplantation *(BLT).* At evaluation (*): VR versus SLT, $p < 0.05$; VR versus BLT, $p < 0.001$. At six months (□), VR versus SLT, $p < 0.001$, VR versus BLT, $p < 0.001$. (+) VR Eval versus VR 6 mo, $p < 0.001$.

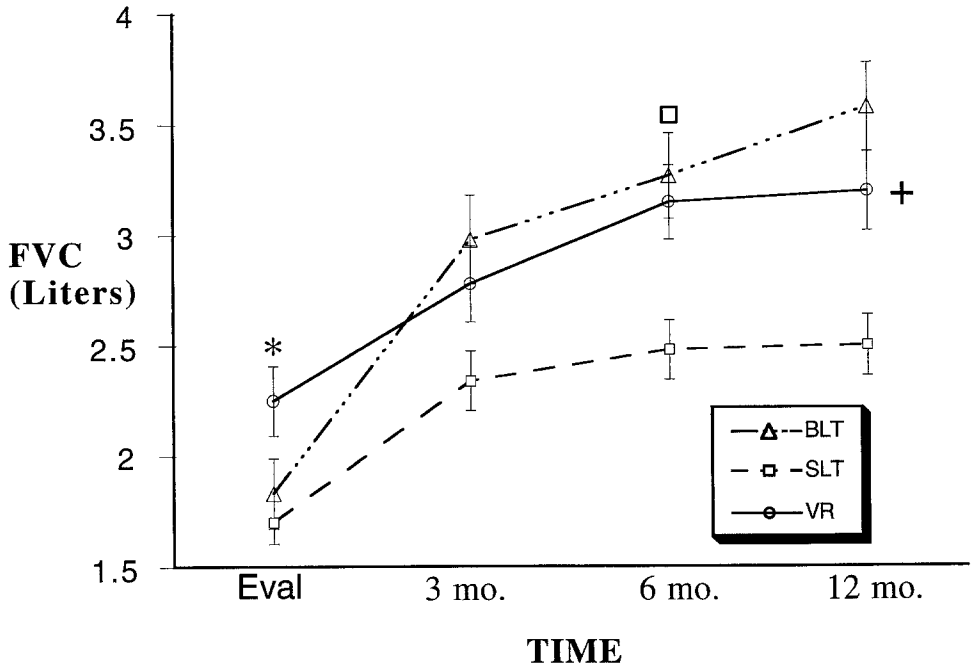

Fig. 3. Forced vital capacity *(FVC)* before and after volume reduction *(VR),* single lung transplantation, *(SLT),* and bilateral lung transplantation *(BLT).* At evaluation (*): VR versus SLT, $p < 0.001$; VR versus BLT, $p < 0.001$. At 6 months (□), VR versus SLT, $p < 0.001$; VR versus BLT, not significant. (+) VR Eval versus VR 6 mo, $p < 0.001$.

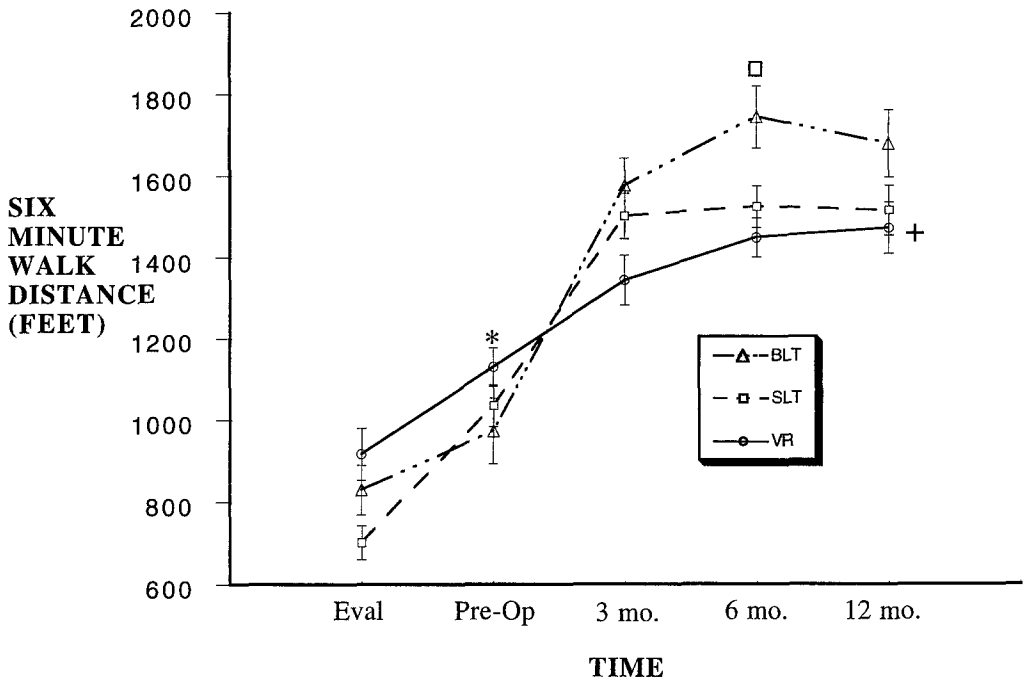

Fig. 4. Comparison of 6-minute walk distance before and after volume reduction *(VR),* single lung transplantation *(SLT),* and bilateral lung transplantation *(BLT).* At evaluation (*): VR versus SLT, not significant; VR versus BLT, $p < 0.05$. At 6 months (□), VR versus SLT, not significant; VR versus BLT, $p < 0.001$. (+) VR Eval versus VR 6 mo, $p < 0.001$.

in the volume reduction group who by virtue of age and FEV_1 less than 20% were "transplant eligible." Ten patients have been followed up for 3 months and seven patients for 6 months after their operation (Table IV). Preoperative FEV_1 (0.55 L, 20% of predicted), 6-minute walk distance (1098 feet), and room air oxygen tension (64 mm Hg) in these patients were comparable with those of both transplant groups. Postoperative improvement as measured by FEV_1 and 6-minute walk distance in these 12 patients paralleled that of the total volume reduction group. At 6 months, postoperative FEV_1 increased by 59% over preoperative baseline values and 6-minute walk distance by 33%.

Discussion

Transplantation and volume reduction are suitable options in the treatment of selected patients with advanced emphysema. Transplantation leads to impressive improvement in physiologic measurements, exercise ability, and gas exchange. Although the improvement in these parameters after volume reduction may be less dramatic, it is nonetheless significant and maintained in intermediate follow-up examinations. Although volume reduction does not restore normal exercise capability, it does remove limitations on routine activities, usually with freedom from oxygen dependency. Our experience suggests that (1) volume reduction is a suitable alternative in selected patients eligible for transplantation; (2) volume reduction provides an earlier treatment option in patients who may require transplantation at some future date; (3) volume reduction is the only surgical treatment available to patients who are not current or future transplant candidates. There are patients who do not fulfill criteria for volume reduction and for whom transplantation remains the only choice for surgical therapy. It is important to note that the majority of patients with emphysema are not candidates for volume reduction or transplantation. As always, patient selection is critical.

The concept of downsizing a hyperinflated, emphysematous lung and delaying or avoiding transplantation rests on the assumption that volume reduction provides symptomatic relief from dyspnea and its associated disability and that this therapeutic effect persists long enough to justify the risks of the operation. We have found that the beneficial response to volume reduction lasts for the duration of our limited follow-up. In selected patients who

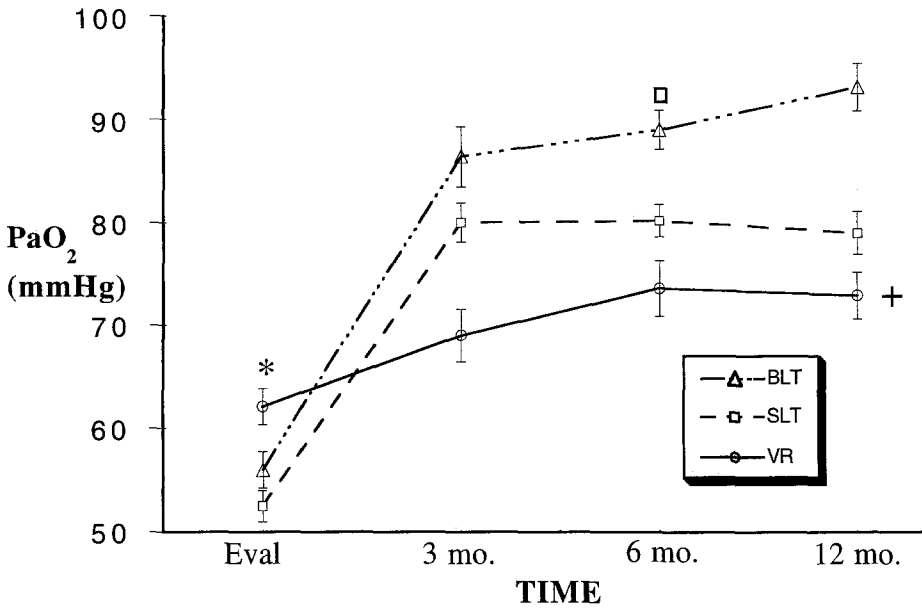

Fig. 5. Comparison of arterial oxygen tension *(Pao_2)* before and after volume reduction *(VR)*, single lung transplantation *(SLT)*, and bilateral lung transplantation *(BLT)*. At evaluation (*): VR versus SLT, $p < 0.001$; VR versus BLT, $p < 0.05$. At 6 months (□), VR versus SLT, $p < 0.001$; VR versus BLT, $p < 0.001$. (+) VR Eval versus VR 6 mo, $p < 0.001$.

fulfilled transplant criteria, volume reduction also resulted in improvement comparable with that of the overall group of patients having volume reduction. Provided this degree of improvement can be maintained over 2 to 4 years, volume reduction will evolve into an alternative or additional therapy for patients with emphysema, permitting a satisfactory quality of life and delaying or eliminating the need for a transplant operation in some patients.

We are satisfied at present with our ability to identify the ideal candidate for volume reduction. Patients with severe thoracic hyperinflation, a flattened diaphragm, and an immobile chest wall have the greatest likelihood of improvement in diaphragmatic and chest wall mechanics. Heterogeneity of disease provides "target" areas for resection. Furthermore, we believe that preoperative reduced ventilation to the less diseased regions of lung contributes to impaired gas exchange and that postoperative redistribution of ventilation accounts for the improved arterial oxygen tension (reduced ventilation/perfusion mismatch) observed in our volume reduction group. Selection of the larger group of patients with less than ideal criteria is not so clear. Severe hypoxemia, hypercarbia, or marked reduction in FEV_1 may exclude a patient from volume reduction if only a moderate degree of hyperinflation or heterogeneity is present.

Table III. *Oxygen requirement*

	VR	*SLT*	*BLT*
Preop.			
At rest	45% (15/33)	100% (39/39)	100% (25/25)
With exercise	88% (29/33)		
3 mo			
At rest	12% (4/33)	2.5% (1/39)	0%
With exercise	30% (10/33)		
6 mo			
At rest	9% (3/33)	0%	0%
With exercise	21% (7/33)		

VR, Volume reduction; *SLT*, single lung transplantation; *BLT*, bilateral lung transplantation.

In patients eligible for transplantation, volume reduction avoids the inevitable complications of cyclosporine, azathioprine, and corticosteroid immunosuppression. Furthermore, it eliminates the necessary monitoring of rejection by periodic pulmonary function testing and transbronchial biopsy. Physiologic parameters of lung function are less improved by a pneumoplastic procedure. For a patient with a predicted preoperative FEV_1 of 15%, a postoperative improvement of 79%, as achieved in our series, would result in a predicted FEV_1 of 27%.

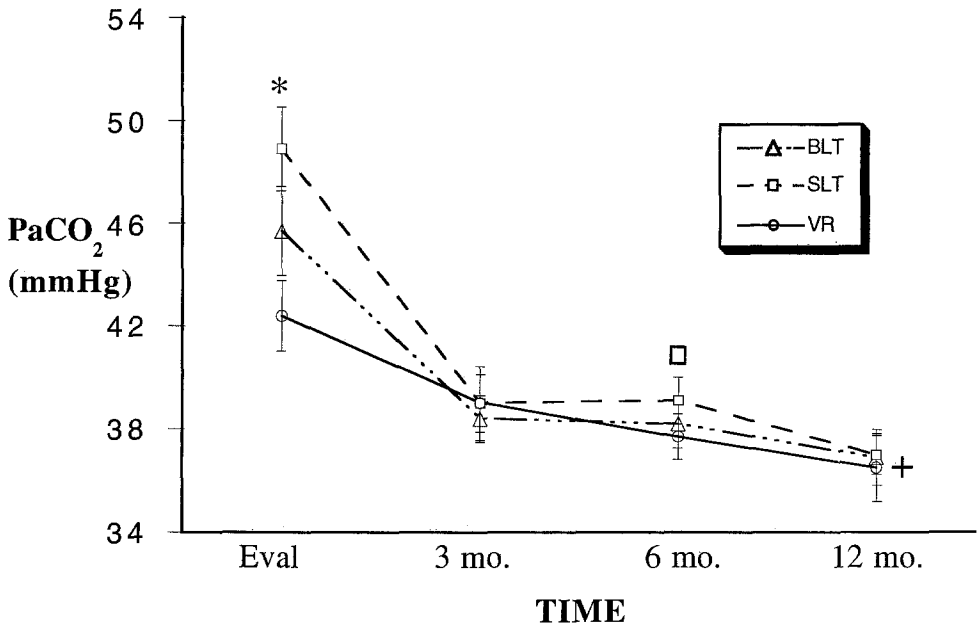

Fig. 6. Comparison of arterial carbon dioxide tension *($PaCO_2$)* before and after volume reduction *(VR)*, single lung transplantation *(SLT)* and bilateral lung transplantation *(BLT)*. At evaluation (*): VR versus SLT, $p < 0.001$; VR versus BLT, $p < 0.05$. At 6 months (□), VR versus SLT, not significant; VR versus BLT, not significant. (+) VR Eval versus VR 6 mo, $p < 0.05$.

Table IV

	Preop. (n = 12)	*3 mo (n = 10)*	*6 mo (n = 7)*
FEV_1 (% predicted)			
Total VR	0.72 (25)	1.19 (43)	1.29 (45)
VR-LT cand.	0.55 (20)	0.90 (34)	0.88 (32)
6-min walk (ft)			
Total VR	1131	1345	1449
VR-LT cand.	1098	1265	1457
Po_2 (mm Hg)			
Total VR	62	69	74
VR-LT cand.	64	76	73

FEV_1, 6-minute walk distance, and room air arterial oxygen tension *(Po_2)* in lung transplant *(LT)* candidates undergoing volume reduction *(VR)* compared with values in the total volume reduction group.

Although this may be less than that achieved by transplantation, exercise tolerance as measured by 6-minute walk distance in these patients was almost as good as after transplantation. However, in any particular patient the lower the preoperative FEV_1, the more ideal with respect to all other criteria for volume reduction the candidate should be.

Several investigators have demonstrated impairment of postoperative exercise tolerance in lung transplant recipients, which persists during the first 2 years after the operation.[13, 14] This impairment was not due to reduced gas exchange or ventilation. Furthermore, diaphragmatic function was not found to be impaired after lung transplantation.[15] The limitations are thought to be related to peripheral factors and physical deconditioning. These findings indicate that transplant recipients do not make full use of their restored lung function and that even the smaller increment of spirometric improvement achieved by volume reduction may be sufficient in many patients to allow unlimited daily activities. The first patients who underwent volume reduction were as a group not as limited as the pretransplantation population, because we selected patients cautiously while the response to the operation was not thoroughly known. Mean FEV_1 in patients operated on since then has dropped to 0.61 L (22% of predicted) and resembles that of the transplant population more closely.

Patients with advanced emphysema are often severely limited by dyspnea long before their lung function has deteriorated to the point that they become transplant candidates. We have performed volume reduction for debilitating symptoms, even when the FEV_1 does not meet transplant criteria. Both FEV_1 and the degree of hypoxemia are used as important selection criteria in transplant candidates, but not in volume reduction. We believe that volume reduction will not preclude subsequent trans-

plantation, although we have not yet performed transplantation in a patient who has undergone volume reduction surgery. We have successfully performed transplantation in many patients with fibrous obliteration of the pleural space as a result of underlying disease or previous thoracic surgery. We anticipate that technical difficulty encountered after volume reduction surgery will be similar. Volume reduction may therefore prolong life and may even be used as a means to delay transplantation. A delayed transplant date also offers the hope of improved immunosuppression in the future.

Many patients with diffuse emphysema are not candidates for transplantation because of age or coexisting disease. For these patients, volume reduction is the only surgical therapy offering palliation. Of the 33 patients in our study, 12 were not eligible for transplantation because of age and two because of coexisting disease. Almost half of our patients (42%) therefore had no alternative other than continued medical therapy. These were all patients who met the other selection criteria for volume reduction, that is, hyperinflation or severe heterogeneity of disease. We have demonstrated that in carefully selected patients volume reduction can be conducted with safety and with the expectation of satisfactory functional results.

Many patients with emphysema do not fulfill criteria for volume reduction. We advise against the operation in the presence of uniformly severe parenchymal destruction, inasmuch as this will likely result in an inferior outcome. This is particularly true for patients without hyperinflation who have preserved diaphragmatic excursion. In addition, patients with other coexisting lung abnormalities, bronchitis, bronchiectasis, and prior thoracic procedures are poor candidates for bilateral volume reduction surgery.

Our preliminary experience indicates that in selected patients volume reduction is an effective treatment strategy. It provides a useful alternative to lung transplantation in some cases. Indeed in many respects it is a preferable option. We await with interest the results of longer term follow-up in these patients.

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Discussion

Dr. Joseph I. Miller *(Atlanta, Ga.).* One year ago in New York Drs. Cooper and Patterson presented a landmark paper on the surgical management of emphysema, revitalizing Brantigan's operation of lung volume reduction for emphysema. It is appropriate that 1 year later their functional results be reported. I would like to make several comments, raise two questions, and point out two areas of potential concern.

The authors have correctly identified the ideal patient as one with hyperinflation, a flattened diaphragm, and target areas of heterogenicity of generalized emphysema, the so-called gas-trapping areas. It is important that we remember this principle as we head into the third year of the reemergence of this operation.

Physiologic improvement is believed to be due to improvement of chest wall mechanics by a restoration of diaphragmatic function and improved elastic recoil of the lung.

In the selection process for lung volume reduction, the authors have not defined limits in regard to spirometric values, hypoxia, or hypercarbia. In the original presentation by Dr. Cooper, the mean carbon dioxide tension was approximately 44 mm Hg with a high of 54 mm Hg. In visiting our institution, Dr. Cooper recently commented that he had operated on a number of patients with a carbon dioxide tension in the 70s.

I believe that the audience should not go away thinking that hypercarbia and age are not significant factors in the preoperative selection process. The majority of complications occur in the hypercarbic group with a carbon dioxide tension greater than 50 mm Hg and an age greater than 70 years. I would caution surgeons to be extremely careful in the selection process regarding these two parameters. To date, we have limited ourselves to a cutoff of 50 mm Hg for carbon dioxide tension and 75 years for age.

The rehabilitation goals—being able to achieve a targeted goal of 30 minutes on the bicycle and 30 minutes on the treadmill—cannot be overemphasized. Conditioning is perhaps the most important aspect of the entire program.

Dr. Gaissert has shown improvement in the three groups in terms of dyspnea index, spirometric values, and 6-minute walk. In each, the functional results in the transplant groups were better than those in the lung volume reduction group, the functional results being approximately 50% in the lung volume reduction group compared with the transplant groups.

The authors have correctly pointed out that lung volume reduction avoids the long-term complications of immunosuppression, and it may be an alternative surgical therapy for some individuals who are not candidates for transplantation. The cost differential alone is not insignificant. In our own locale, the average cost of single lung transplantation is $200,000 to $225,000. The average cost of our first 10 lung volume reduction operations was approximately $55,000, and this does not take into account the $25,000 to $30,000 a year in immunosuppressive drugs required.

In terms of functional results, our own data support those of Dr. Gaissert and his colleagues in St. Louis. Indeed our program is modeled entirely after the St. Louis program. Among our first 20 patients we obtained follow-up to 6 months in only four. However, the spirometric values, the oxygenation, and the 6-minute walk results are almost identical, showing that the results are easily reproducible, as pointed out by Dr. Gaissert.

There have been a number of late-night calls among those of us doing this type operation as we go through previously uncharted postoperative waters. The problems have included panic attacks, distended colon and cecum, and the development of pulmonary hypertension and right heart failure in patients with previously acceptable values.

I have two questions. The authors state that they advise against surgery in the presence of uniformly severe parenchymal disease. I assume that they mean a lack of defined target areas on perfusion scanning. If I am not mistaken, a number of patients in their first 20 had uniform generalized emphysema with fairly equal perfusion distribution between left and right sides and between upper and lower lobes. Will the authors please clarify their statement that they have operated on a few of these with equal distribution with fairly good results?

Second, I would like to know the type of complications the authors have noted.

I conclude with these two statements. This is a new and exciting operation, and I hope it will pass the 2-year time test that I think most of us believe will be a benchmark in determining its value.

Second, I would caution against starting out on this type of operation without appropriate backup resources. The postoperative course of these patients is totally uncharted waters and presents complications that I have not seen in my 21-year practice experience. We can proceed with cautious optimism inasmuch as the initial results are highly encouraging; however, this type of lung volume reduction program should not be undertaken lightly.

Dr. Gaissert. I thank Dr. Miller for his comments. Panic attacks have been seen by the residents taking care of these patients, but I think they are probably related to shortness of breath and to the postoperative strain. These patients require close, careful attention after the operation and do not at all compare with patients who have had lobectomy or pneumonectomy.

We believe that an even distribution of ventilation and perfusion certainly should raise the caution of the surgeon. If any other indicators in that particular patient speak against surgical treatment, such as an elevated carbon dioxide tension or a severe degree of hypoxemia, we would certainly refrain from considering the patient for volume reduction. However, we would not regard ventilation-perfusion distribution as a contraindication to performing the operation so long as the anatomic criteria were fulfilled.

Dr. Randas J. V. Batista *(Campina Grande do Sul, Brazil).* We share the same philosophy of volume reduc-

tion for improvement in organ function, but we apply the principle to the heart. Allow me to describe the case of a 74-year-old man with Chagas' disease in whom we reduced the volume of the heart.

The patient had a very low ejection fraction that would have indicated heart transplantation had he not been too old for that operation. After cardioversion, a ventriculogram was obtained, which showed a high peripheral vascular resistance. He was receiving a high dose of inotropic agents, so we transferred him to the operating room on an emergency basis.

We start our incision in the apex of the heart and extend it to the anterior papillary muscle, which is irrigated by the diagonal branch, and then to the mitral anulus. Thus we reduce the volume of the heart to improve function, just as you reduce the volume of the lung. The second incision involves excision. We excise through the apex of the heart, going down to the base of the posterior papillary muscle, which is irrigated by the circumflex branches, and finish the excision at the mitral valve. At that point we find live muscle, not scar tissue. The marginal artery emerges in this piece of muscle, and lots of clots are seen. We can excise more muscle in the anterior area. We do not crossclamp the aorta.

We use through-and-through full-thickness sutures (2-0 Prolene sutures; Ethicon, Inc., Somerville, N.J.) in two layers. The first layer is to hold the muscles together, and the second layer is to provide hemostasis. If mitral repair is necessary, there is good exposure to repair the papillary muscles. In the past 11 years we have used this operation in 130 patients.

At the end of the operation the patient described here was no longer receiving inotropic agents, he was starting to urinate, and peripheral perfusion was good. The only cardiac medication that he is taking in the postoperative period is nitroprusside (Nipride).